SEARCH FOR DIRECT CP VIOLATION IN $K^\pm \to \pi^\pm\pi^+\pi^-$ DECAYS BY NA48/2 [a]

I. Mikulec [b]
Österreichische Akademie der Wissenschaften, Institut für Hochenergiephysik, A-1050 Wien, Austria

First preliminary measurement of the direct CP-violating parameter A_g by the NA48/2 experiment at CERN SPS is presented. Using more than 1.6 billions of charged kaon decays into three charged pions, the charge asymmetry in the $K^\pm \to \pi^\pm\pi^+\pi^-$ Dalitz plot slope, A_g, has been measured to $A_g = (0.5 \pm 3.8) \times 10^{-4}$. This result is more than an order of magnitude more precise than results of previous experiments.

1 Introduction

Violation of the CP symmetry, and especially direct CP violation in the decay amplitude, due to its subtle nature, is an important window into physics beyond Standard Model (SM).

It took more than three decades since the discovery of CP violation in the neutral kaons by Christenson, Cronin, Fitch and Turlay [1], until direct CP violation was definitively established. After an unconfirmed indication by NA31 [2], KTeV and NA48 have demonstrated in the late 90's with high significance that direct CP violation exists in the decays of neutral kaons into two pions [3,4]. In the year 2001, B-factory experiments Babar and Belle have found CP violation in the system of neutral B mesons [5] and last year also the direct CP violation in B-decays has been demonstrated [6].

In order to explore possible non-SM enhancements to heavy-quark loops which are at the core of direct CP-violating processes, all manifestations of direct CP violation need to be experimentally studied and measured. In kaons, besides the already measured parameter ε' in $K_L \to \pi\pi$ decays, the most promising complementary observables are decay rates of GIM sup-

[a] Talk given at XXXXth Rencontres de Moriond, ElectroWeak Interactions and Unified Theories, La Thuile, March 2005.

[b] On behalf of the NA48/2 collaboration.

pressed rare kaon decays [7] which proceed through flavor-changing neutral currents and the asymmetry between K^+ and K^- decays into three pions.

The $K^\pm \to 3\pi$ matrix element is usually described in a polynomial expansion of two Dalitz variables u and v:

$$|M(u,v)|^2 \propto 1 + gu + hu^2 + kv^2 + O(u^3, v^3) \tag{1}$$

where $|h|, |k| \ll |g|$ and

$$u = \frac{s_3 - s_0}{m_\pi^2} \qquad \text{and} \qquad v = \frac{s_2 - s_1}{m_\pi^2} \tag{2}$$

with $s_i = (p_K - p_{\pi i})^2$ and $s_0 = \sum s_i/3$ $(i = 1, 2, 3)$. Index $i = 3$ stands here for the odd pion [c]. Slope parameters g can differ between the K^+ and K^- only due to direct CP violation [d]. SM predictions for the corresponding asymmetry

$$A_g = \frac{g^+ - g^-}{g^+ + g^-} \tag{3}$$

vary between few 10^{-6} to few 10^{-5} [8]. An analogous asymmetry of integrated decay rates, A_Γ, is expected to be more than an order of magnitude smaller. Several experiments [9] have searched for the asymmetry A_g. The precision reached in both $\pi^\pm\pi^+\pi^-$ and $\pi^\pm\pi^0\pi^0$ decay modes so far is at the level of few 10^{-3}. Existing theoretical calculations involving processes beyond SM [10] predict substantial enhancements of the asymmetry A_g partially within reach of the NA48/2 experiment.

NA48/2 is an extension of the original experimental program of the experiment NA48 at the CERN SPS which has successfully accomplished the main goal to establish and measure the direct CP violation in the decays of neutral kaons into two pions [3]. The primary aim of the NA48/2 extension [11] is to measure the parameter A_g in $\pi^\pm\pi^+\pi^-$ and $\pi^\pm\pi^0\pi^0$ modes to $\sim 2 - 4 \times 10^{-4}$.

NA48/2 took data in two periods. In total, during the 50 day run in the year 2003 and the 60 day run in the year 2004 about 4 billions of $K^\pm \to \pi^\pm\pi^+\pi^-$ and about 200 millions of $K^\pm \to \pi^\pm\pi^0\pi^0$ decays have been collected and taped. The total recorded data volume amounts to about 200 TB. This paper describes the analysis and the preliminary result based on about 1.6 billions of $K^\pm \to \pi^\pm\pi^+\pi^-$ decays taken during the first 2003 run.

2 Description of the Experiment

NA48/2 deploys a novel system of two simultaneous charged beams with opposite charges. This allows to record decays of K^+ and K^- at the same time achieving a significant cancellation of systematic effects in the charge asymmetry measurement.

The beams (Fig. 1) of charged particles are derived from protons from the SPS which impinge with an intensity of about 7×10^{11} protons per 5 s pulse on a beryllium target of 2 mm diameter and 40 cm length at a zero angle of incidence. The central momentum of 60 GeV and the momentum bite of ± 3 GeV are then selected symmetrically for positively and negatively charged particles in the first achromat unit which splits the two beams in the vertical plane and recombines them on the same axis. Then both beams pass through a series of focusing quadrupoles and are again split and cleaned in the second achromat. The second achromat together with the KABES detector [12] serves also as a beam spectrometer. The K^+/K^- production ratio is about 1.8 (the analysis is independent of this ratio).

After the second achromat both beams follow the same path. After passing the cleaning and the final collimators they traverse the entire $\sim$114 m long decay volume superimposed

[c] Other two, even, pions have equal charges.

[d] Due to absence of mixing only direct CP violation is possible in decays of charged kaons.

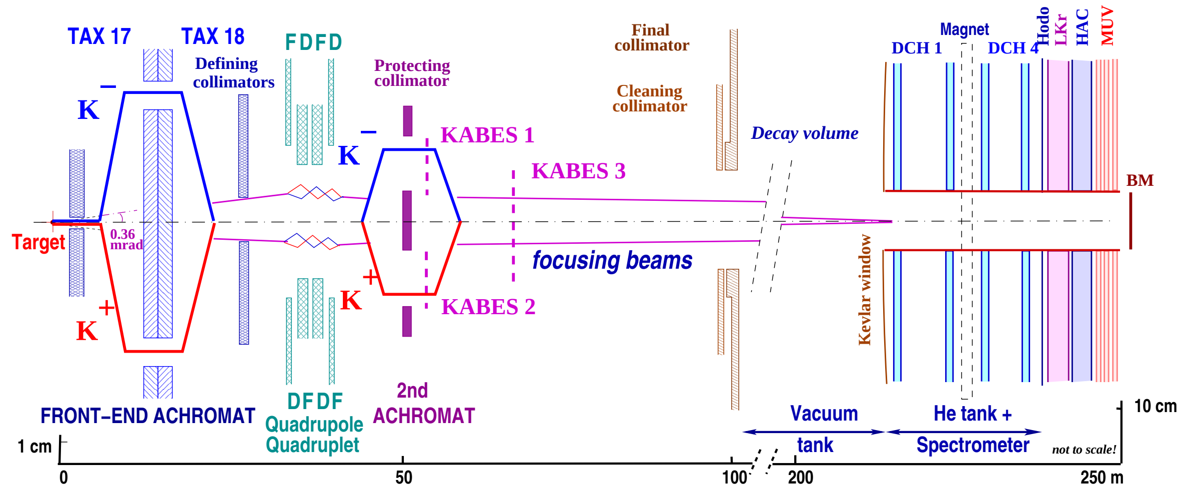

Figure 1: Lateral view of the NA48/2 beam and detector. The vertical scale is strongly enhanced.

with a precision of about a millimeter. This superposition symmetrises the acceptances and contributes to the reduction of systematic biases. The decay region is comprised in a vacuum tank. The whole detector apparatus downstream the decay volume is almost identical to the NA48 experimental setup.

The detector used for the reconstruction of $K^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$ decays is the magnetic spectrometer. The spectrometer is housed in a tank filled with helium gas at atmospheric pressure separated from the vacuum tank by a KEVLAR window. A thin evacuated beam tube, traversing the centre of the detector, allows the undecayed beam particles to continue in vacuum. Two drift chambers are located before and two after the central dipole magnet which induces a horizontal transverse momentum kick of about 120 MeV/c to all charged particles. The drift chambers have an octagonal shape with an area of about 4.5 m^2. Each is made of four sets of two staggered planes of sense wires oriented along four 45° directions. The momentum resolution of the magnetic spectrometer is $\sigma(p)/p = 1.0\% \oplus 0.044\% p$ with p in GeV/c units.

The $K^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$ decays are triggered with a two-level trigger system. At the first level, the rate is reduced to few hundreds of kHz by requiring at least two hits in a scintillator hodoscope placed behind the magnetic spectrometer. The second level trigger, which consists of hardware coordinate builders and a farm of asynchronous microprocessors, reconstructs tracks using data from the drift chambers. At least two tracks are required to converge within 5 cm in the decay volume. In the majority of the analysed data, level one triggers rejected by this condition are examined further and accepted even if only one track is reconstructed by the second level trigger. In this case it is required that this track is kinematically incompatible with a $\pi^{\pm}\pi^{0}$ decay, assuming the decaying kaon had momentum of 60 GeV/c and was moving along the beam axis. The resulting trigger rate is about 10 kHz.

The description of other components of the NA48 detector apparatus can be found elsewhere[3].

3 Measurement Method

The measurement is based on comparing the u-distributions of K^+ and K^- decays. In case of the $\pi^{\pm}\pi^{+}\pi^{-}$ final state, given the actual value[13] of $g = (-0.2154 \pm 0.0035)$, the ratio $N_{K+}(u)/N_{K-}(u)$ is proportional with sufficient precision to $(1+\Delta g u)$. $A_g = \Delta g/2g$ is extracted from a linear fit to the ratio $N_{K+}(u)/N_{K-}(u)$.

The presence of magnets both in the beam sector (achromats, focusing quadrupoles, etc.) and in magnetic spectrometer introduces an unavoidable charge asymmetry of the apparatus. In order to equalise local effects on K^+ and K^- beams the achromat and quadrupole polarities were reversed during data taking on an approximately weekly basis. The polarity of the spectrometer magnet has been reversed every day [e]. The whole approximately two-week cycle represents a super-sample which is treated in the analysis as an independent data unit. In the period of 2003, four super-samples have been collected.

Each super-sample contains four $K^+ \to \pi^+\pi^+\pi^-$ and four $K^- \to \pi^-\pi^-\pi^+$ samples with different combination of achromat and spectrometer magnet polarities. The ratio $R(u)$ is obtained as a product of four $N_{K+}(u)/N_{K-}(u)$ ratios:

$$R(u) = R_{US}R_{UJ}R_{DS}R_{DJ} \approx \overline{R}(1 + 4\Delta g u) \quad (4)$$

where U represents a configuration in which K^+ beam runs through the upper beam path in the achromats and D the lower. The index S represents spectrometer magnet polarity in which decay products having the same charge as the corresponding beam are deflected to the right with respect to the direction of the beam (towards the Saleve mountain) and J to the left (towards the Jura mountain). A linear fit to Eq. 4 results in two parameters, normalisation $\overline{R}$ and Δg from which A_g is extracted.

The quadruple ratio technique in Eq. 4 completes the procedure of magnet polarity reversal. It allows a three-fold cancellation of systematic biases:

- beam line local biases cancel between K^+ and K^- samples in which the beam follows the same path;
- local detector biases cancel between K^+ and K^- samples deflected toward the same parts of the detector;
- as a consequence of simultaneous beams, global time-variable biases cancel between K^+ and K^- samples.

This method is independent on the relative size of the samples with different magnet configurations. On the other hand, the statistical uncertainty depends on the statistically weakest of the eight samples involved in Eq. 4. Further reduction of systematic biases especially due to presence of stray permanent magnetic fields (earth's field, vacuum tank magnetisation) is obtained by maintaining azimuthal symmetry in the acceptance.

Using the method described in this section, the result remains sensitive only to time variation of asymmetries in experimental conditions which have a characteristic time smaller than corresponding field-alternation period.

Due to superposition of the two beams the measurement does not need a Monte Carlo calculation of the acceptance. Nevertheless, detailed GEANT-based [14] Monte Carlo simulation has been developed as a tool for systematic studies. The Monte Carlo simulation includes full detector geometry and material description, simulation of time-variable local drift chamber inefficiencies and time-variations of the beam geometry and drift chamber alignment.

4 Data Analysis

Several stages of compaction and filtering were necessary in order to reduce the data to a size suitable for the analysis. At least three reconstructed tracks in magnetic spectrometer, loose

[e] During the data taking in the year 2004 the period of the spectrometer magnet reversal has been decreased to few hours.

acceptance and quality cuts as well as at least one good reconstructed three-track vertex are required in the pre-selection phase.

Tracks are reconstructed from hits in drift chambers using the measured magnetic field map rescaled according to the recorded current in the analysing magnet of the spectrometer. Chambers and individual wires are aligned using data collected in special runs in which muons were recorded with spectrometer magnet off.

The three-track vertex is reconstructed using track segments from the first half of the spectrometer correcting the extrapolations for the small magnetic fields due to magnetisation of the vacuum tank and from the earth's field. Using measured momenta and track directions obtained at the vertex the invariant mass of three pions is calculated. The stray-field correction, calculated based on a three-dimensional field map measured in the entire vacuum tank, reduces the azimuthal variation of the reconstructed invariant mass of $\sim$1 MeV/c^2 by an order of magnitude.

The invariant mass resolution is about 1.7 MeV/c^2. Since the decay $K^\pm \to \pi^\pm\pi^+\pi^-$ is the dominant three-track decay, the sample is background free. The tails of the invariant mass distribution are dominated by events in which one of the three pions decayed and the spectrometer reconstructs the track of the resulting muon [f]. Using Monte Carlo simulations, the tails due to pion decays have been shown to be highly symmetric between K^+ and K^- samples. Only far tails are rejected by the cut $|m_{\pi\pi\pi} - m_K| < 9$ MeV/c^2, where m_K is the PDG value of the charged kaon mass [13]. The systematic uncertainty due to pion decays, limited by the statistical precision of the generated Monte Carlo samples, is $\delta(\Delta g) = 0.4 \times 10^{-4}$.

The most important feature determining the acceptance is the beam tube traversing the centre of all drift chambers. In order to securely exclude the central insensitive areas, all three tracks are required to cross the first drift chamber at least 11.5 cm from the beam centre and the last drift chamber at least 13.5 cm. The latter cut takes into account the additional beam deflection of about 2 cm with respect to the centre of the last drift chamber due to the spectrometer magnet. This important acceptance cut is related to the beam centre rather than to the centre of the detector. The reason is, that the beam optics can control the mean beam position only to about $\pm$1 mm. The actual beam position is continuously monitored to a much better precision by calculating the momentum-weighted centre of gravity of three pions at first and at the last drift chamber planes, independently for K^+ and K^-. In addition to the time variation of the beam position, also the dependence of the beam position on the kaon momentum ($\sim \pm$1 mm in horizontal and $\sim \pm$1 cm in vertical direction) is taken into account. In this way the K^+ and K^- acceptances cancel entirely and no Monte Carlo calculation is needed to correct for their difference. A conservative limit on residual systematic uncertainty, $\delta(\Delta g) = 0.5 \times 10^{-4}$, was determined by studying the sensitivity to various acceptance definitions.

The measurement of the pion momenta is based on the knowledge of the magnetic field in the spectrometer magnet and on the tracking information from the drift chambers. The relative variations of the current in the magnet can be controlled down to about 5×10^{-4}. Smaller variations are continuously corrected by forcing the mean reconstructed $\pi\pi\pi$ mass to the PDG kaon mass [13] with relative precision of about 10^{-5}. This is done by scaling the measured track momenta symmetrically for positively and negatively charged tracks. As this effect is charge symmetric, by collecting K^+ and K^- simultaneously it cancels in the ratio $R(u)$.

A difference between the reconstructed $\pi\pi\pi$ invariant masses of K^+ and K^- is an unambiguous measure of a residual horizontal drift chamber misalignment. An uncorrected horizontal shift of the chambers can lead to a charge-antisymmetric mis-measurement of the momenta. Observing this invariant-mass difference as a function of time, revealed significant, up to about 0.2 mm, movements of the drift chambers between individual alignment runs. Correcting the measured momenta by $p' = p(1 + q\beta p)$, where q is the sign of the track charge and β is proportional

[f] In order to avoid charge-dependent biases, the muon tracks are not vetoed by the NA48 muon-veto system.

Table 1: Preliminary limits on systematic and trigger uncertainties on Δg in units of 10^{-4}.

Acceptance and beam geometry	0.5
Spectrometer alignment	0.1
Analysing magnet	0.1
Pion decay	0.4
Calculation of u and fitting	0.5
Pile-up	0.3
Total systematic uncertainty	0.9
Trigger efficiency - level 1	0.4
Trigger efficiency - level 2	0.8
Total trigger uncertainty	0.9

to the difference of the invariant mass between K^+ and K^- [g], reduces the effect to a practically negligible level [h].

A potential source of systematic bias is the trigger. Inefficiencies of different trigger components are studied and measured using control samples from low bias triggers collected along with the main triggers. The rate-dependent parts of inefficiencies are assumed to be charge symmetric (simultaneous beams). The inefficiency of the first level was measured to be small, about 7×10^{-4} and stable in time. No correction is applied and an uncertainty of $\delta(\Delta g) = 0.4 \times 10^{-4}$, limited by the statistics of the control sample, has been attributed to this part. The rate independent inefficiency of second level trigger varies with time between 0.2 and 1.8%. The main source of this inefficiency are local drift chamber inefficiencies which are more important in the trigger than in the reconstruction due to reduced redundancy. All samples are corrected by the measured second level trigger efficiencies as a function of u. The uncertainty is fully dominated by the statistics of the control samples.

Further sources of systematic effects were studied and evaluated. Bias due to resolution and the calculation of u was studied by changing the way u-variable is calculated from measured track momenta. Using odd or even pion tracks changes the resolution as a function of the position in the Dalitz plot (u, v). Additional studies were performed excluding various parts of the Dalitz plot. The preliminary result quoted in this paper is obtained from the fit restricted in the u-interval between -1 and $+1$. Effects due to pile-up of signals from different kaons due to high instantaneous intensity were studied by comparing samples with different amounts of recorded extra tracks close in time to the event. Charge-asymmetric material effects have been found negligible by studying amount and composition of the material in front of and in the chambers and taking into account pion spectra. Track charge misidentification was evaluated from events with three tracks of equal charge. Table 1 summarises all systematic uncertainties attributed to the result.

5 Preliminary Result and Outlook

The preliminary result presented in this paper is obtained from the full sample of reconstructed $K^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$ decays collected by the experiment NA48/2 during the data taking period of the year 2003. Three independent analyses, which agree within uncorrelated uncertainties, have been performed and averaged. The result is calculated separately for each of the four super-samples and then combined taking into account correlated systematic uncertainties (Table 2).

[g] A shift of last drift chamber by 1 μm corresponds to about 1.5 keV change in the invariant mass.

[h] In the 2004 data-taking the alignment runs were performed on a more frequent, weekly, basis.

Table 2: Measurement of Δg in units of 10^{-4} in individual super-samples and the corresponding statistics. Only uncorrelated uncertainties, statistical uncertainty combined with the uncertainty from the level 2 trigger efficiency, are quoted.

Super-sample	$K^+ \to \pi^+\pi^+\pi^-$ in 10^6	$K^- \to \pi^-\pi^-\pi^+$ in 10^6	$\Delta g \times 10^4$
0	431	240	0.5 ± 2.4
1	258	144	2.2 ± 2.2
2	253	141	-3.0 ± 2.5
3	95	53	-2.6 ± 3.9
Total	1036	577	-0.2 ± 1.3

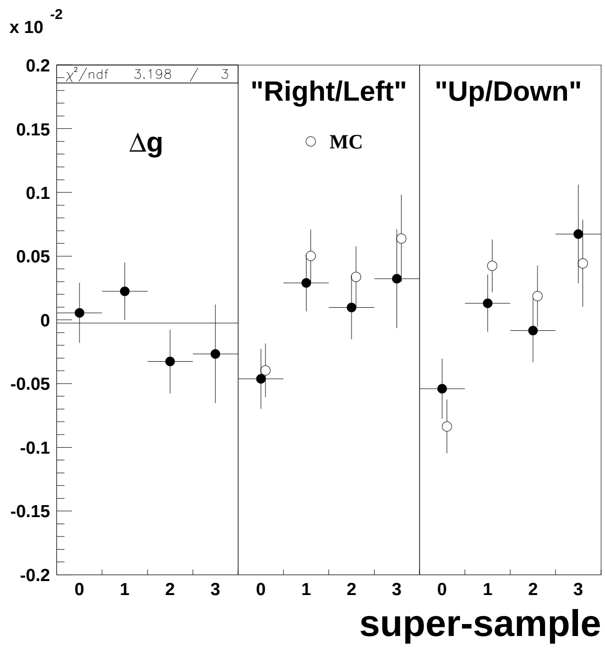

Figure 2: Left: Measurement of Δg in four super-samples. Middle, Right: Detector resp. beam-line asymmetries which cancel in the Eq. 4 and their comparison to the Monte Carlo simulation.

The measurement stability as a function of super-sample is shown in the left part of the Fig. 2. All four measurements are compatible with each other with $\chi^2/ndf = 3.2/3$. As a systematic check, in the middle part of this figure, the quadruple ratio in Eq. 4 is rearranged such that instead of four K^+/K^- ratios, four ratios of samples in which even pions are deflected to the right are divided by samples with even pions deflected to the left in the spectrometer magnet. In this case, the physical quantity Δg cancels and the result is expected to be equal to zero in the absence of any residual left-right detector asymmetries. Similarly, the right part of the Fig. 2 reflects the asymmetry of the two beam paths. These control asymmetries, which cancel at first order in Eq. 4, show that the cancellation of systematic biases due to residual time variable imperfections in the apparatus is at the level of few 10^{-4} and therefore second order effects are negligible. Moreover, the comparison with Monte Carlo simulations shows that all these apparatus asymmetries are understood in terms of local inefficiencies and beam optics variations.

The combined preliminary result from all four super-samples is

$$\Delta g = (-0.2 \pm 1.0_{stat.} \pm 0.9_{stat.(trig.)} \pm 0.9_{syst.}) \times 10^{-4} \quad (5)$$

Converted to the asymmetry using the PDG value of the Dalitz slope g [13]:

$$A_g = (0.5 \pm 2.4_{stat.} \pm 2.1_{stat.(trig.)} \pm 2.1_{syst.}) \times 10^{-4} \quad (6)$$
$$= (0.5 \pm 3.8) \times 10^{-4} \quad (7)$$

This result is compatible with no CP violation and with Standard Model predictions but has more than an order of magnitude better precision than similar previous measurements[9]. Further improvements are expected in future. The uncertainty due to the trigger can be significantly improved by deeper study of inefficiencies as well as by emulating the trigger in Monte Carlo simulations. Also some of the systematic uncertainties can be improved by more detailed studies of involved effects and by using data collected in the period of 2004. These data are being analysed and will significantly reduce the statistical uncertainty by more than doubling the total sample.

NA48/2 has collected also about 200 millions of $K^{\pm} \to \pi^{\pm}\pi^{0}\pi^{0}$ decays. This decay mode is disfavored statistically due to its lower branching ratio and lower acceptance. On the other hand, this disadvantage is practically completely compensated by more favorable population of the Dalitz plot leading to an expected statistical uncertainty on A_g comparable to that of the $\pi^{\pm}\pi^{+}\pi^{-}$ decay mode.

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